Large-Scale Visible and Infrared Optical Phased Arrays in Silicon Nitride

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Abstract: Large-scale optical phased arrays at 635nm and 1550nm wavelengths are demonstrated with aperture sizes up to $4\times4\text{mm}^2$. A diffraction limited spot with a record $0.021^\circ\times0.021^\circ$ divergence and output powers as high as 400mW are shown.

OCIS codes: (130.3120) Integrated optics devices; (250.5300) Photonic integrated circuits; (280.3640) LIDAR.

1. Introduction

Nanophotonic optical phased arrays have recently gained great interest in applications such as LIDAR [1,2], free-space communication [3,4], image projection [5], and holographic displays [6]. Long-range power transmission for LIDAR or data-communication systems require output beams to have a small diffraction angle, i.e. far field spot size, and high power. Both can be addressed with a large aperture size and power distribution network. However, nonlinearity-induced phase changes and material loss in silicon limit the scalability and power output of silicon-based arrays.

In this work, large-scale passive silicon nitride based optical phased arrays at infrared (IR) and visible wavelengths are demonstrated. Silicon nitride is utilized for its high power capability and robustness to fabrication induced phase variation. The demonstrated IR phased array operates at a wavelength of 1550nm and has 1024 antennas, resulting in a $4\times4\text{mm}^2$ aperture size. This is the largest aperture optical phased array to date by an order of magnitude [7]. A main beam output power of 400mW is achieved and the array is shown to be near diffraction limited with a FWHM spot size of $0.021^\circ\times0.021^\circ$. In addition, using the same silicon nitride fabrication process and design architecture, the first large-scale visible phased array at 635nm is also demonstrated with an aperture size of $0.5\times0.5\text{mm}^2$.

2. Ultra-Large Infrared Phased Array

A photograph of the $4\times4\text{mm}^2$ IR phased array is shown in Fig. 1(a). The phased array was fabricated on a 300mm silicon wafer using 193nm immersion lithography on a PECVD deposited silicon nitride layer. The phased array utilizes a 10-layer binary tree distribution network of cascaded 1×2 multi-mode interference (MMI) splitters in order to distribute the input light to 1024 grating-based antennas. Figs. 1(b-c) are InGaAs IR camera images when the camera

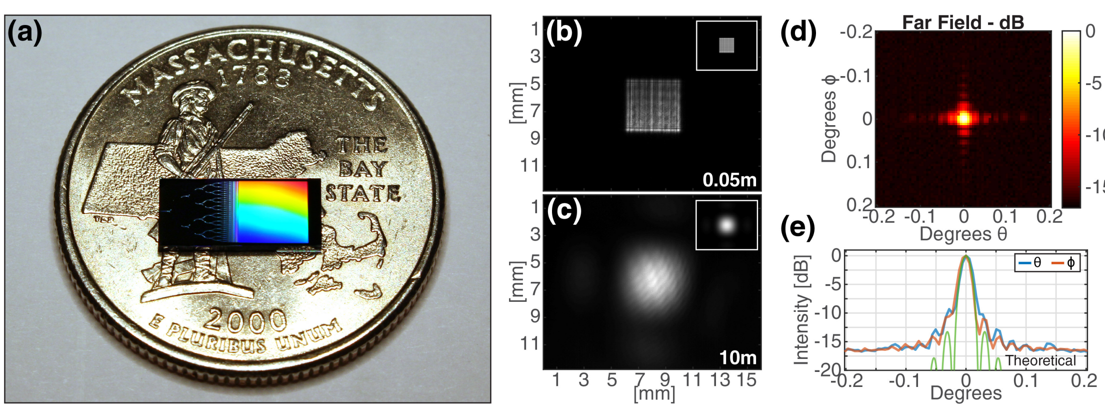

Fig. 1. (a) Photograph of the $4\times4\text{mm}^2$ IR phased array after fabrication. (b) Main beam intensity measurement after approximately 0.05m and (c) 10m propagation. Insets show Fresnel propagation simulations in the same domain. (d) Far field of the main beam of the IR phased array on a log scale. (e) Far field intensity cuts of the phased array along the array, θ, and antenna, ϕ, dimensions.

is directly placed in the path of the main beam at 0.05m and 10m away from the phased array. After a propagation of 10m, the beam has not increased greatly in size due to the large aperture. Fig. 1(d) shows the measured far field of the array and intensity cuts along the array and antenna dimensions are plotted in Fig. 1(e). The expected sinc function is observed in both the antenna and the array dimensions with a side lobe suppression of 10dB. The measured FWHM spot size was $0.021^\circ \times 0.021^\circ$, whereas the theoretical diffraction limited spot size is $0.019^\circ \times 0.019^\circ$. This ultra-small spot size is over an order of magnitude smaller in area than the previous demonstration in [7] and allows for long-range transmission. A power of 400mW was measured in the main beam of the array with a 9.1W off-chip input power.

3. Visible Phased Array Demonstration

Since the demonstrated IR phased array was fabricated in silicon nitride, the same platform can be utilized for visible wavelengths and a phased array was designed for 635nm. Fig. 2(a) is a visible camera image of a $0.5\times0.5\text{mm}^2$ visible phased array when light is input into the chip showing the waveguides and MMI tree. Fig. 2(b) shows the output of the array on a white card. The measured far field of the main beam of the visible array is shown in Fig. 2(c). The measured FWHM spot size was $0.064^\circ \times 0.074^\circ$ whereas $0.063^\circ \times 0.063^\circ$ is the theoretical diffraction limit of the square aperture. Figs. 2(d-e) show intensity cuts of the spot along the array and antenna dimensions. A side lobe suppression of 8.7dB is measured in the array dimension. Multiple strong side lobes are observed indicating the presence of phase variation in the MMI tree. This is likely due to side-wall roughness that interacts with the more confined visible waveguide mode. Designing the array for a TM polarized input could minimize the interaction with the side-wall roughness.

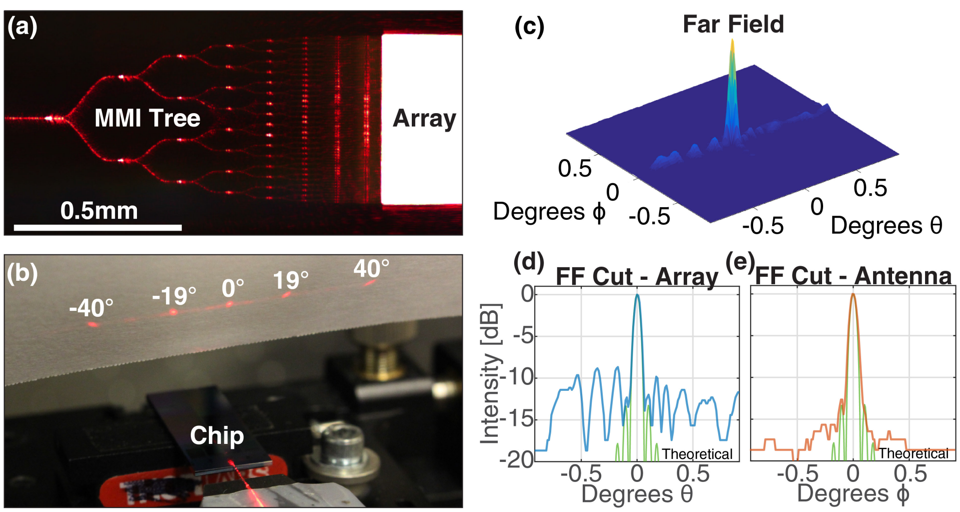

Fig. 2. (a) Saturated visible image of the 635nm $0.5\times0.5\text{mm}^2$ phased array. (b) Photograph of the visible phased array output on a white card. (c) Far field of the visible array. (d-e) Far field intensity cuts of the visible phased array along the array and antenna dimensions.

In conclusion, we have demonstrated the largest optical phased array to date with an aperture of $4\times4\text{mm}^2$. A main beam output power of 400mW was measured with a spot size of $0.021^\circ \times 0.021^\circ$. This demonstration shows the scalability of optical phased arrays and is promising for on-chip LIDAR applications. Future work in silicon nitride on silicon platforms can utilize the demonstrated distribution network followed by a transition to a silicon layer for element phase shifting. Furthermore, utilizing the same architecture, we have demonstrated the first large-scale visible phased array. This phased array is the first of its kind and shows that large-scale silicon nitride based photonics is possible at visible wavelengths.

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